Comparative Assessment of Power Absorption in Heads of Adults and Children Exposed to the Radiation of Cellular Phones at 1800 MHz

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Summary. The aim of this work is to examine the differences in power absorption in the brain of adults and children exposed to the radiation of mobile phone terminals at 1710 MHz. To this end, simulations using the Finite-Difference Time-Domain (FDTD) method have been carried out to study the interaction between heterogeneous anatomically correct models of the human head and a linear or helical monopole mounted on the top of a metal box representing a realistic mobile communication terminal. The study includes computations of specific absorption rates (SARs) inside the human head and the total power absorbed by the head. Emphasis is placed on the comparative assessment of power absorption characteristics in heads of adults and children as well as on the effect of various parameters such as the age-related changes in dielectric properties and the usage distance between the user’s head and the mobile terminal.

Keywords: biological effects of electromagnetic radiation, dosimetry, helical and linear antenna, FDTD method

Introduction

It is indisputable that in recent years, cellular phones and mobile wireless communication systems have characterized the technological development of the whole world. This has resulted in public concern about the potential health hazards of RF electromagnetic fields that are emitted by these devices. To protect mobile telephone users, all the cellular terminals compliance tests consist in checking that the Specific Absorption Rate (SAR) levels due to mobile telecommunications terminal are below the limits recommended by international safety guidelines (FCC OET BULLETIN 65, 1997; CENELEC, 1997; International Commission on Non-Ionizing Radiation Protection, 1998; IEEE Standard C9.51, 1999). Moreover, children’s use of mobile telephones is growing, while the dosimetric results in children’s heads are still inconsistent. In 2001, the U.K. Independent Expert Group on Mobile Phones (IEGMP) reported that, on the basis of the evidence currently available, there is no need for the general population to be worried about the use of mobile phones (http://www.iegmp.org.uk, 2001). However, the Group recommended that children less than 16 years of age should be discouraged from using mobile telephones since they may absorb more energy from a given telephone than adults do because of their smaller heads, thinner skulls and higher tissue conductivity. Additionally, in 2004, the Group lowered the reference child age to 10 years (Independent Expert Group on Mobile Phones, 2004).

In 1996, Gandhi et al. using Finite Difference Time Domain (FDTD) analysis compared the 1-gr averaged SAR values induced in 5 years old, 10 years old and adult head models exposed to a mobile handset. The children models were derived by scaling an adult head model based on their relative height and weight. The authors reported an increase of 50% in the 1-gr averaged spatial peak SAR in the 5 years old head model for a quarter wavelength (λ/4) monopole antenna mounted on a metal box at 835 MHz. The authors also studied the effect of using widely disparate tissue properties...
reported in the literature (Gandhi et al., 1996). In 1998, Schönborn et al. mentioned that modeling children heads by merely scaling-down adult heads may represent a tentative approximation. They analyzed models based on anatomical data drawn from magnetic resonance imaging (MRI) scans of an adult, a 7 years old and a 3 years old individuals, using the Finite Integration Technique (FIT). Their analyses concerned exposure to linear dipole antennas, operating at 900/1800 MHz, and showed no substantive difference in SAR absorption between the adult and child models. However, this result is also open to question, as it is not known how representative these three individuals were of their respective group. Moreover, the authors examined the possible differences in the SAR values due to electrical parameters as well as to distance between the terminal and the user (Schönborn et al., 1998). Wang and Fujiwara (2003) presented an evaluation of the two studies, which reported increasing or decreasing exposure trends for children depending on the design of the radiation system and the normalization of the outputs. Hadjem et al. (2005) using FDTD analysis and two realistic child head models isotropically and anisotropically scaled down versions of the adult one, concluded in no great differences in SAR values between the adult and the children’s models. It is noticeable that the dosimetric results presented by different groups are quite inconsistent. However, it is quite usual that different research groups even using very similar methods may present contradictions in the simulation results due to different simulation preconditions (Nikita et al., 2000).

From the foregoing discussion, it is clear that there is a lot of controversy about the determination of the age-related changes in head SAR levels from mobile telephones. The objective of the present paper is to examine potential parameters that affect the electromagnetic absorption in human head models of adults and children exposed to mobile terminals operating at 1710 MHz.

The size of the head model can have a significant impact on the radiated output of the antenna by altering the coupling of the antenna to the head, which in turn changes the antenna input impedance (Wang and Fujiwara, 2003). Thus, in the present study, power absorption by an MRI-based adult head model and its appropriately scaled down version representing a 10-years old child, is examined.

The distance between the mobile terminal in normal use and the biological object constitutes a decisive factor that can influence the absorbed electromagnetic power by the human head. This parameter is determined, among others, by the spacing caused by the intervening ear. By performing measurements of the thickness of a slightly compressed ear in a sample of 52 persons, presumably all adults, a distribution of ear thickness ranging from 3 to 10 or more mm, with a mean value of about 5 mm was reported in Kuster et al. (1997). The growth of the ear with age was also examined in Ito et al. (2001) and a reasonable estimate for relative age changes was obtained by averaging the relative age changes in the other dimensional parameters. In the present work, the effect of the intervening ear and age-related changes is investigated by performing simulations for varying separation distance between human head models and mobile handsets.

Furthermore the effect of tissue properties on SAR distributions is also examined in the present work, since a substantial increase in dielectric properties of the tissues of small animals has been reported for younger animals (Peyman et al., 2001). The decrease in the dielectric properties with age may be due to changes in the water content and the organic composition of tissues with age (Dawkins et al., 1979). Even though the corresponding data are not available for human tissues, the implications for the assessment of children exposure seem to be quite interesting.

Finally, the design of the radiating element can play an important role in the coupling between mobile terminal and user’s head. Since linear antennas represent the most widely employed antenna model in previous handset devices, while modern handsets are usually equipped with helical type antennas, a comparative evaluation of power absorption in adult and child heads exposed to either linear or helical antennas has also been carried out.

The effect of the above mentioned factors on the peak SAR levels induced in human head models, is examined in the present paper. Results are produced for heterogeneous anatomically correct models of adults and children heads exposed to a linear monopole or a helix monopole mounted on the top of a metal box representing a realistic mobile communication terminal. For the simulations, the FDTD method has been used, due to its simplicity and its ability to treat highly non-homogeneous structures.
Computational method

FDTD simulations have been carried out for a heterogeneous anatomically correct model of the human head, using the commercially available software package XFDTD. A rectangular computational grid, based on the Yee cell, with a spatial resolution of 1.25 mm and the total field formulation have been used, while PML absorbing boundary conditions with 8 PML layers have been employed (Berenger, 1994). The boundaries were placed 30 cells away from the nearest scatterer. Converged results have been assured by using 12 time periods. The helix geometry has been approximated in the FDTD grid as a rectangular helix of wires using perfect conducting cell edges.

Once the electric field inside the head model is computed, then the SAR at any point inside the head can be calculated as,

$$\text{SAR} = \frac{\sigma}{\rho} |E_x^2| + \frac{\sigma}{\rho} |E_y^2| + \frac{\sigma}{\rho} |E_z^2|$$

(1)

where $\sigma$ (S/m), $\rho$ (kg/m$^3$) represent the specific conductivity and the mass density of the cubic element of the FDTD grid and $|E|$ is the magnitude of the x electric field component at the same cubic element.

Using an interpolation scheme, calculations for averaged SAR values over a reference mass $M = 1$ g and 10 g have been carried out. Cubical spaces centered on a cell are formed and the mass and average SAR of the sample cubes are found. The size of the sample cube increases until the total enclosed mass exceeds the reference mass $M$. The sample cube increases in odd-numbered steps (1 x 1 x 1, 3 x 3 x 3, 5 x 5 x 5 etc) to remain centered on the desired cell. The sample cube must meet some conditions to be considered valid. The cube may contain some non-tissue cells, but it cannot contain an entire side or corner of non-tissue cells. If the cube is found to be invalid, the averaging for the center cell stops and the same procedure is performed for the next center cell.

Although FDTD is able to model anatomically detailed human head structures, significant difficulties can be encountered in modeling antenna structures not conforming to the used grid, such as the helical antenna. The accuracy of FDTD simulations has been checked against results produced by an accurate semi-analytical technique based on the combination of dyadic Green’s functions theory and the Method of Moments (Green/MoM) for canonical problems involving layered spherical human head models exposed to linear or helical type dipole antennas (Koulouridis et al., 2004; Koulouridis and Nikita, 2004; Nikita et al., 2000).

Head and antenna models

A realistic adult head model developed from MRI scans of a human head has been studied. This anatomically correct head model has been provided by Bradford University, has a spatial resolution of 1.25 mm and consists of 13 different tissues (Olley and Excell, 1995). Electrical characterization of the head tissues has been based on literature data (Gabriel et al., 1996).

In order to obtain a child’s head model from the adult one, a conversion factor has been used. Considering that the height of the average male adult is 176 cm and its weight is 71 kg, the dosimetry handbook recommends that for an average 10-year old child the height and weight would be 138 cm and 32.5 kg respectively (Durney et al., 1986). Therefore, all dimensions in realistic adult head model have been changed by a factor $(176/138, 32.5/71)^{1/2}$. Although, a realistic child head model cannot be derived as a simple scaling down of the corresponding adult one, at the moment, MRI head scans concerning children are poor, making difficult the modeling of anatomically correct child head models. Thus, in the present study, the realistic child head model has been produced from the adult one by first changing the spatial resolution of the adult head model by the above mentioned factor and then by resampling the altered head model into 1.25 mm grid size.

Moreover, in the framework of the present study, an attempt has been made to examine the relation between the dielectric properties of the tissues characterizing the head model and the deposition of electromagnetic energy within biological matter. The published literature on the age related variation of the conductivity of the head tissues is too sparse and it only concerns rats and small animals. For instance, rat tissue conductivity decreases significantly in the first 25 days of life, and then stabilizes thereafter (Peyman et al., 2001). However, there is no correlation with human development changes in the tissues dielectric properties. As an attempt to interpret the data concerning rats and other small animals to human, there have been studies, which attributed the higher conductivity
in tissues of young animals to a larger number of ions (http://www.iegmp.org.uk, 2001). However, some studies relate the change in tissue dielectric properties with water content. Biological materials having a large amount of bound water might be expected to present higher values of dielectric properties and therefore a relatively higher absorption of electromagnetic power for frequencies below which the free water starts to disperse, i.e. below about 5 GHz (Dawkins et al., 1979). There is strong indirect evidence based on total body water content indicating that the dielectric properties of children do not significantly differ from adults after the first year of life (Anderson, 2003). However, any clear differences in the parameters for the same tissues in adults and children could lead to significant changes in absorption. Even though the information about the variation in the dielectric properties with age is not available for the human tissues, the implications for the assessment of human head exposure could be quite interesting. Thus, simulations for head models with a ±10% variation in the dielectric properties have been carried out in the present work.

As far as the mobile terminal is concerned, a quarter-wavelength linear monopole or a normal mode helical antenna operating at 1710 MHz mounted on the top corner of a handset box have been examined. The geometrical details of the linear antenna are: wire thickness $2w = 2.5$ mm, length $\lambda/4 = 2.1875$ mm and feeding gap $d = 1.25$ mm. The geometrical details of the examined helical antenna are: helix radius $a = 2.5$ mm, pitch $B = 1.25$ mm, wire thickness $w = 0.1$ mm, turns $L = 4$, and feeding gap $d = 0.2$ mm (Cerri et al., 1999). Either of the above described phone radiating elements is mounted on the top corner of a metal handset box as shown in Fig. 1. The dimensions of the metal box are $12 \times 5.5 \times 2$ cm and its front face is covered with a low loss dielectric $\varepsilon_r = 2.7 - j0.016$, with a thickness of 2.5 mm. Point E in Fig. 1 corresponds to the projection of the ear canal to the dielectric front face of the handset. In the FDTD grid, the helix antenna monopole has been constructed as a rectangular helix of wires with horizontal sections consisting of four cells and a vertical step of one cell.

### Numerical results and discussion

The effect of the usage distance, and the dielectric properties variations on the power absorption by the head of an adult and a 10-year old child has been studied. The accuracy of the results obtained by the FDTD method has been extensively checked for several canonical exposure problems as described in detail in Koulouridis and Nikita (2004).

![Figure 1](image.png)

**Figure 1.** (a) Handset equipped with a quarter-wavelength linear monopole (b) handset equipped with a helix monopole. Dimensions in mm. Point E corresponds to the projection of the ear canal.
Variation of the usage distance

In order to study the effect of the separation distance on the coupling between realistic MRI-based head models of an adult and a 10-year old child exposed to the handset shown in Fig. 1(b), FDTD simulations have been carried out for distances \( D = 0, 2.5, 5, 7.5, 10 \) mm between the ear of the MRI based head model and the mobile terminal metal box. The handset is placed on a vertical position and the largest distance was chosen having in mind that it is not quite usual for a user to hold the mobile terminal at a distance greater than 1.0 cm.

The maximum values of local SAR, SAR averaged over 1 g or 10 g of tissue, were computed and are shown in Fig. 2 while in Fig. 3 the power absorbed by the user’s head is shown. By comparing the results for the largest separation distance \( (D = 10 \text{ mm}) \) to those for the handset in direct contact with the ear \( (D = 0 \text{ mm}) \), a 78% reduction in the local SAR values is observed for both adult and child cases and a 70–72% reduction in SAR averaged over 10 g for both models as well. As far as the total absorbed power is considered, a 66% of the terminal antenna input power is absorbed by the adult or the child head model for \( D = 0 \) mm. As the separation distance becomes larger \( (D = 10 \text{ mm}) \) the absorbed power reduces by a factor of 52–54% for the child and the adult head model, respectively.

In Fig. 4, local SAR variation along x-axis, that is from ear-to-ear, is presented in adult and child head models in the proximity of the handset of Fig. 1(b), placed on the left of the diagram for \( D = 0 \text{ mm} \) and \( D = 10 \text{ mm} \). Although the SAR values at points lying close to the head surface are similar for adults and children, noticeable differences can be observed at various depths from the head surface.

\[
\text{Maximum SAR} = f(\text{distance})
\]

![Graph showing SAR values for varying distances](image)

*Figure 2. Peak SAR values in adult/child head models exposed to the handset of Fig. 1(b) for varying separation distance. The antenna input power is 125 mW.*
Figure 3. Total power absorbed by adult/child head models exposed to the handset of Fig. 1(b) for varying separation distance. The antenna input power is 125 mW.

Figure 4. Local SAR variation along x-axis in the adult/child head models exposed to the handset of Fig. 1(b), placed at a distance $D = 0$ mm or $D = 10$ mm away from the head model.

Variation of the dielectric properties of head tissues

Next, the effect of dielectric properties characterizing the tissues of the head model on the power absorption by the user's head is examined. To this end, separate simulations have been carried out for head models characterized by dielectric properties with a ±10% variation. The values of tissues mass density remain constant. The heterogeneous anatomically correct adult and child models of the human head were placed at a distance $D = 0$ mm from the handset (i.e. in contact with the ear).

The corresponding results are presented in Figs. 5 and 6. By comparing the case of lower to that of higher dielectric properties values, a reduction of the order of 7.8–6.5% in the local SAR values can be noticed for adult and child head models as the dielectric properties reduce. The corresponding reduction in SAR averaged over 10 g is of the order of 7.8–6.5%, as well. Similarly, a slightly reduction is observed in the total power absorbed by the head with increasing dielectric properties.

The effect of dielectric parameters variation on the local SAR distributions is shown in Fig. 7 for the local SAR variation along x-axis. From the
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**Figure 5.** Peak SAR values in adult/child head models exposed to the handset of Fig. 1(b) for dielectric properties variation ±10%. The antenna input power is 125 mW.

**Figure 6.** Total power absorbed by adult/child head models exposed to the handset of Fig. 1(b) for dielectric properties variation ±10%. The antenna input power is 125 mW.
Figure 7. Local SAR variation along x-axis in adults/child head models in the proximity of the handset of Fig. 1(b), placed at a distance $D = 0$ mm away from the head model. Dielectric properties variation $-10$ and $10\%$.

Presented results it can be observed that as the dielectric properties become higher the SAR values become slightly higher.

**Comparative evaluation of the results according to the used radiating element**

In this section, a comparative study is presented in order to assess the differences in power absorption by the human head model, due to different radiating elements (linear/helical). Simulations have been carried out examining the coupling of the realistic adult or child head model irradiated by either a quarter-wavelength linear monopole, or a normal mode helix monopole, mounted on the top corner of a metal handset box (Fig. 1) for fixed separation distance $D = 0$ mm.

The maximum values of local SAR, SAR averaged over 1 g or 10 g of tissue and the power absorbed by the head have been computed and are comparatively shown in Figs. 8 and 9. In order to facilitate direct comparison of the results, the calculated values of SAR and absorbed power are shown again for the helical type.

Figure 8. Peak SAR values in adult/child head models exposed to the handset of Fig. 1(a), (b). The antenna input power is 125 mW.
monopole against the corresponding ones produced by the linear monopole.

It can be noticed that although local SAR values observed in the child’s head are lower than the corresponding ones in the adult’s head, similar or even slightly higher values of SAR averaged over 10 g are observed in the child’s head for both radiating elements. In general, significantly larger SAR values are induced by the helical radiating elements as compared to those induced by the linear one due to the greater field concentration produced by the physically shorter helical antenna. Moreover, as far as the power absorbed by the user’s head is concerned, a 57–63% of the linear antenna input power is absorbed by the adult or child head, while the corresponding percentage for the helical antenna is 65%.

**Conclusion**

The objective of the present study was to evaluate the dependence of the power absorption and the maximum SAR levels produced by cellular phone antennas operating at 1710 MHz in anatomically detailed head models upon age-related parameters. To this end, an MRI-based adult head model and its appropriately scaled down version representing a 10-year old child head have been used. The investigated parameters included the usage distance between the head model and the mobile terminal as well as the dielectric parameters characterizing head tissues. For the simulations, the Finite Difference Time Domain (FDTD) method was used. Furthermore, the effect of the type of the phone radiating element has also been studied, by considering two types of terminal antennas, i.e. a linear and a helical antenna. Results produced have revealed that similar levels of absorbed power between adults and children head models are observed. Furthermore, a significant reduction in the SAR values with increasing usage distance and with decreasing values of head tissues dielectric properties was observed. It is important to note that higher maximum SAR values are produced by the helical antenna as compared to the corresponding ones for the linear antenna due to the greater field concentration by the physically shorter helical antenna.

**References**


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